Geo-mechanical and rheological modelling of upper crustal faults and their near-surface expression in the Netherlands

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Abstract

The pattern of fault reactivation, basin deformation and concentration of seismicity along the main trans-Netherlands fault zone, located NW–SE across the centre of the Netherlands, indicates that this zone is a major zone of weakness. Gravity modelling reveals after back-stripping of the sedimentary succession a distinctive continuous positive anomaly that can be explained by lithospheric sources. This zone of weakness is therefore likely to have a major influence on the tectonic processes currently active in the Netherlands region. We give a review of the tectonic history of the Netherlands and then present the results of a quantitative study of the reactivation of basin boundary faults and the influence on the surrounding basin. Well-data, balanced and back-stripped cross-sections are used to constrain the lithosphere rheology. The lithosphere rheology modelling results show a weak coupling between upper crustal deformation and the subcrustal lithosphere. A finite element modelling approach focussing on the upper crust is carried out in which the basin boundary faults are assigned various dips. The modelling results indicate that, for continuous reactivation of basin boundary faults, the presence of both a pre-existing weakness and a reduced friction angle is required. The latter implies that large displacements accommodated by primary faults cannot be directly attributed to the relative weakness of these faults compared to the secondary faults, which is in close accordance with inferences from trenching. A reduced friction angle has a significant effect on lithospheric strength and appears to be the major controlling factor in the reactivation of basin boundary faults. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Netherlands are located at the southeastern end of the Central North Sea Graben, part of a failed rift system, and on the northern edge of the Variscan mountain chain, which occurs close to the Netherlands’ southern border (Sintubin, 1999). The Tertiary Lower Rhine embayment, located southeast of the Netherlands, is the northern part of the central and most prominent major tectonic feature of northwestern Europe, the Cainozoic Rhine Graben rift system (Ziegler, 1990).
World Stress Map data, including data from Frikken (1999) (Fig. 1) indicate that the stress regime of northwestern Europe is presently characterised by an overall N–S/NW–SE compressional stress field, controlled by ridge push forces from the Mid-Atlantic Ridge and the collision of Africa and Europe (Goes et al., 2000; Gölke and Coblentz, 1996). These stresses are sufficiently large in the Netherlands to cause significant neo-tectonic deformation (e.g. see Houtgast and van Balen, 2000) and earthquakes with magnitudes up to 6.3 (e.g. Camelbeeck and Meghraoui, 1998), causing considerable damage to the infrastructure. The largest recorded earthquake near Roermond (13-4-1992) has a local magnitude of 5.8 and a moment magnitude of 5.4 (Camelbeeck et al., 1994).

High intraplate compression, generated as a result of Alpine compression and plate tectonic reorganisations in the northern Atlantic region interacting with the pre-existing basin framework, has been shown to play a key role in the large-scale lithosphere response in northwestern Europe (Van Wees and Cloetingh, 1996; Ziegler et al., 1998; Cloetingh et al., 1999; Frikken, 1999). These intraplate deformational events have also had an important impact on the record of vertical motions, resulting in anomalous patterns of subsidence and differential uplift (Cloetingh et al., 1990; Frikken, 1999), interfering with coeval erosional events induced by climatic change. The Roer Valley Graben of the southeastern Netherlands, is the locus of the highest level of observed seismicity in the Lower Rhine embayment and has experienced an anomalous acceleration in subsidence since the Oligocene (Zijerveld et al., 1992) and is characterised by Moho shallowing (Rijkers and Duin, 1994; Remmelts and Duin, 1990).
A characteristic feature of Late Neogene intraplate deformation in northwestern Europe is the localisation of deformation along the pre-existing tectonic fabric. Rheological case studies of Phanerozoic basin evolution demonstrate that the interplay of stresses and tectonic fabric is marked by existence of weak zones permanently prone to reactivation (Van Wees and Stephenson, 1995; Ziegler et al., 1995; Frikken, 1999). The principle point in this tectonic context is the relatively rapid succession of extension and inversion events and the presence of relatively weak lithosphere marked by intraplate decoupling in the northwestern European Platform (Fig. 2, Cloetingh and Burov, 1996). These features play an important role in the spatial and temporal distribution of reactivation in the polyphase basin history (e.g. Reemst and Cloetingh, 2000), and are of key importance for river incision and avulsion (Houtgast and van Balen, 2000; Frikken, 1999; Berendsen and Stouthamer, 2000).

In this paper, we study the relationship between the pre-existing tectonic Mesozoic and Cainozoic basin fabric of the Netherlands and the neotectonic deformation at or near the surface. Initially, we review the bulk basin structural fabric, focussing on the neotectonically active fault systems of the Netherlands and surrounding areas. Subsequently, we address the reactivation kinematics in terms of quantitative rheological and geomechanical modelling of the crust lithosphere system of selected basins in the Broad Fourteens Basin and Roer Valley Graben, respectively (Fig. 1).

Our study demonstrates the intrinsic role of lithosphere memory in the spatial and temporal localisation of the current intraplate deformation in the Netherlands. In particular, border faults appear to be main foci of enhanced deformation, compatible with the observed patterns in seismicity (Camelbeeck and Meghraoui, 1998; Geluk et al., 1995). Results of detailed geomechanical modelling for the in-depth variations of fault displacements on primary and secondary faults are in close agreement with inferences from trenching in the Lower Rhine graben (Camelbeeck and Meghraoui, 1998).

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Fig. 3. Schematic tectonic map of Avalonia, showing amalgamation of basement terranes in northwestern Europe (simplified and modified after Pharoah, 1999; Meisner et al., 1994). Italics: D = Germany, F = France, GB = Great Britain, IR = Ireland, S = Sweden, SC = Scotland, N = Norway, NL = Netherlands. Grey areas represent the present-day location of continents.
Fig. 4. Pre-Permian subcrop map of the Netherlands (after Van Adrichem Boogaart and Kouwe, 1993).
2. Palaeozoic tectonic framework for the Netherlands and adjacent areas

Recent multi-disciplinary studies have shed much new light on the Palaeozoic amalgamation of northwestern Europe and corresponding terrane boundaries (e.g. Meissner et al., 1994; Soper and Hutton, 1984; Pharoah, 1999). A recently compiled basement map of the Trans-European Suture Zone shows that the Netherlands is located in the approximate centre of the East Avalonian block (Fig. 3, Pharoah, 1999). This terrane is assumed to be detached from Gondwana and moved in a northward direction, eventually colliding with Baltica and Laurentia while closing the Tornquist Sea and the Neo-Iapetus Oceans, respectively (Coward, 1995). This collision with Baltica and Laurentia generated composite conjugate marginal sutures and fault structures of zones trending NW/SE and NE/SW, respectively. In the Netherlands area, these zones have a NW/SE trend, including the Lower Rhine Lineament, trending parallel to the main axis of the present-day intraplate stress field in the northwestern European Platform (Fig. 1).

The earliest basin forming events to affect the Netherlands Avalonian basement occurred during the Upper Carboniferous as part of the foreland of the Variscan mountain chain (Ziegler, 1990). These basins developed in a northwestward direction as a result of a lateral shear system associated with clockwise rotation of Caledonian crustal fragments (Coward, 1995). In Late Carboniferous–Early Permian times, the Variscan mountain chain and its foreland were strongly modified as a result of megashear, accompanied by orogenic collapse, intense volcanism and thermal uplift (Ziegler, 1990). This resulted in pervasive uplift and erosion, with local subsidence in the Variscan foreland and tearing apart of the Variscan mountain chain. No detailed subsidence analysis determining the amounts of uplift and erosion has been carried out so far. Subsequent, Late Permian, relaxation and extension in the northern edge of the Variscan mountain chain resulted in slip along major NW/SE trending left lateral strike-slip zones and the formation of salt-filled rift or thermal sag basins (Ziegler, 1990; Geluk, 1999; Van Wees and Beekman, 2000) (Fig. 4).

3. Mesozoic and Cainozoic tectonic framework for the Netherlands and adjacent areas

Seismic sections of NW-England (Chadwick and Evans, 1995) reveal two periods of extension, Late Permian and Early Triassic, the latter being the major Permo-Triassic rifting event reported in literature. A similar study by Geluk (1999) also shows evidence for two extensional periods during Late Permian for the Netherlands subsurface. These two periods are associated with either a gravitational collapse or a tearing apart of the Variscan front (Henk, 1999) along a series of NW/SE trending faults, thus creating a series of pull-apart basins in the Netherlands (Frikken, 1999). The NW/SE trending trough displaying maximum Triassic subsidence is oriented approximately perpendicular to the main axis of Permo-Triassic rifting for NW-Europe (Chadwick and Evans, 1995). Explanations for this rectangular rift system, causing a broad triple junction across NW-Europe, generally attest to the interference of the Atlantic and Arctic rift systems, with the major direction trending NE/SW (e.g. the Oslo Graben, Horn Graben and Glückstadt Graben) and the minor direction trending NW/SE (e.g. Sole Pit and Broad Fourteens Basin). Other explanations (e.g. Coward, 1995) involve extension in the Neo-Tethyan Ocean area.

Late Triassic rifting is related to the ongoing extension of the North Atlantic region and is accompanied by local volcanism, e.g. the Central Graben.
Most Triassic basins are asymmetric with W-ward dipping normal faults although this basin shape is not well developed in the Netherlands (Fig. 5). A NW/SE extension, as suggested by Beach (1987), would make the Central Graben amongst other structures, a pull-apart feature in a right lateral shear system. Rifting prevailed contemporaneously with opening of the Atlantic, the strongest pulses occurring during Late Jurassic and Early Cretaceous. Many of the Variscan faults were reactivated during (1) the Early Triassic rifting phase (Figs. 5 and 6), which also triggered diapirism (Griffiths et al., 1995; Rem-

Fig. 6. Basin location map, showing major basin elements, major basin boundary faults (bold) and location of sections in Figs. 5, 7 and 8.
melts, 1995), (2) the Late Jurassic–Early Cretaceous rifting phase and (3) Late Cretaceous and Tertiary intra-plate compressional phases (Chadwick and Evans, 1995; Carter et al., 1995) that affected most of western Europe.

Subsequently, a wide Cainozoic basin developed which till recently was commonly assumed to be almost unaffected by faulting. However, an increasing number of studies have revealed the importance of neo-tectonics and recent vertical motions in areas adjacent to the North Atlantic and the North Sea Basin (Camelbeeck and Meghraoui, 1998; Chalmers and Cloetingh, 2000).

In this paper, we will not discuss these models in detail, but illustrate some aspects of the polyphase deformed tectonic setting in which the Netherlands basins are situated.

The large basinal structures described above, are clearly recognisable in a compilation of 2D sections (Fig. 5 and 6) and comprise from south to north the Roer Valley Graben, which passes laterally into the West Netherlands Basin and then into the Broad Fourteens Basin. This basinal trend is subsequently being offset towards the Central Graben. The sub-basin boundary faults have clearly been reactivated multiple times during phases of subsidence, uplift and erosion (Figs. 5 and 6) (Geluk et al., 1996; Rijkers and Geluk, 1996; Geluk, 1999). Several studies (Brun and Nalpas, 1996; Dronkers and Mrozek, 1991; Nalpas et al., 1995) have shown that compressional movements, acting at a lithospheric scale, induced the reactivation of pre-existing normal (rift) faults, general uplift, erosion and basin inversion.

4. Basinal and tectonic trends for Tertiary and Quaternary deposits

Tertiary deposits in the Netherlands are characterised by a large NNW/SSE basinal structure made up of three inter-connected sub-basins (Fig. 7). These sub-basins are, from south to north, the Roer Valley Graben, the Zuiderzee Basin and the southern tip of the Dutch Central Graben. Between the first and second sub-basin, a structurally complicated ridge is present dissecting the continuous pattern of a basin deepening towards the Central Graben. This ridge consists of, amongst Mesozoic structural features, the Maasbommel High and the IJmuiden High (Fig. 7). Subdivision of Tertiary sediments into a southern and a northern block, tilted southeastwards and northwestwards, respectively, reveals a NW/SE zone following the main trans-Netherlands faults.

The main tectonic features, e.g. the Zuiderzee Basin and the IJmuiden High (Fig. 7), are thought to have formed after the Late Cretaceous–Early Tertiary compressional movements that caused several phases of differential subsidence (e.g. Rijkers and Geluk, 1996; Ziegler 1990). These differential movements are caused by incipient stress release after the collisional coupling between the Alpine and Pyrenean orogenies (Ziegler, 1990; Ziegler et al., 1998).

No large basinal structure is recognised for Quaternary deposits in the Netherlands, although thicknesses of 600 m are observed in wells (Fig. 8). Within these sediments, a main NNW/SSE oriented depositional trend developed, which is coincident with the basinal trend of Tertiary sediments. Subdividing this subtle Quaternary depositional trend into a southern and a northern block, tilted southeastwards and northwetwards, respectively, reveals a NW/SE zone following the main trans-Netherlands faults. Superimposed on this subtle Quaternary depositional pattern are the main tectonic features of the Roer Valley Graben and Zuiderzee Basin.

Geodetic levelling studies (e.g. Groenewoud et al., 1991; Lorentz et al., 1995; Van den Berg et al., 1995) for the Netherlands region suggests significant differential vertical movement of the top of the Pleistocene. The results of these studies point to a general tilting of the Netherlands, with the coastal regions subsiding relative to inland areas.

Vertical motion of the subsurface is thought to occur in response to three principal processes; isostasy, compaction and tectonics. Kooi et al. (1998) attempted to estimate the absolute rate of vertical ground motion caused by each of these processes. Their results suggest that compaction-driven subsidence is restricted to areas where clay deposits of Holocene and Late Tertiary age are abundant, i.e. close to the North Sea. Furthermore, Kooi et al. (1998) interprets more than 50% of the tilting of the Netherlands to be the result of tectonic processes. Hence, isostasy is inferred to cause significantly less than 50% of the observed vertical motions. The
benchmark levelling studies therefore suggest that recent tectonic activity, which has been documented in supposedly tectonically inactive areas, is a major factor influencing current subsidence in the Netherlands region.

5. Reactivation of basin structures and lithospheric memory

Depth maps of two horizons, base Tertiary and base Quaternary, were derived from interpretation of
seismic sections and combined with fault traces, topography and earthquake data to distinguish possible correlations between them (Figs. 7 and 8). Together with geological sections (Fig. 5) these maps reveal a distinct NW/SE zone of weakness, characterised by repeated reactivation of sub-basin boundary faults, following the main trans-Netherlands faults (Fig. 5). Several studies (Brun and Nalpas, 1996; Dronkers and Mrozek, 1991; Nalpas et al., 1995) have shown that the Late Cretaceous–Early Tertiary
compressional movements, resulted in the reactivation of pre-existing normal (rift) faults, general uplift, erosion and basin inversion. Furthermore, the sub-basin boundary faults have been reactivated numerous times in response to lithospheric scale processes (Dronkers and Mrozek, 1991; Geluk et al., 1996; Rijkers and Geluk, 1996). The pattern of fault reactivation, basin deformation and concentration of seismicity along the main trans-Netherlands fault zone indicates that this structure forms a major zone of weakness, possibly at the lithospheric scale. This structure is therefore likely to exert a major influence on the tectonic processes currently active in the Netherlands region (see also Dirkzwager et al., 2000a). In order to assess the nature and importance of pre-existing weak elements, a quantitative analysis...
of the evolution of the trans-Netherlands fault zone and adjacent basins on a lithospheric and upper crustal scale has been carried out.

5.1. Lithosphere rheology modelling of the Broad Fourteens Basin

Several studies on the reconstruction of paleo-rheology (e.g. Braun, 1992; Van Wees and Stephenson, 1995; Van Wees and Beekman, 2000) have resulted in an improved understanding of lithospheric deformation as a function of temporal changes in lithospheric rheology. Paleo-rheology predictions for basins show that a substantial strengthening of the basin can occur a long time after rifting has ceased (e.g. Braun, 1992). This post-rift strengthening may result in preservation of deformation features from the rifting phase within the relic basin. Fig. 9 illustrates this phenomenon for a rifted margin that has similar rheological properties as the present day Lower Rhine Embayment.

In order to quantify the rheological evolution of the Netherlands region and in particular the role of the trans-Netherlands fault zone, a forward modelling study was conducted. The Late Permian to Early Cretaceous Broad Fourteens Basin is a well-studied example of a reactivated basin (van Wijhe, 1987; Dronkers and Mrozek, 1991; Huyghe and Mugnier, 1995; Ziegler et al., 1995; Nalpas et al., 1995; Brun and Nalpas, 1996; Frikken, 1999) and is used here as a representative part of the Netherlands region at large (see Van Wees et al., 1997 for details).

Our analysis utilises a back-stripped well (Fig. 10) constructed with the aid of the balanced cross-section of Huyghe and Mugnier, (1995) and using average lithologies from Van Adrichem Boogaart and Kouwe (1993, 1996). During most of its evolution, the Broad Fourteens Basin is characterised by shallow water depths, typically less than 100 m. In order to simplify the analysis, a water depth of 0 m is assumed for the entire basin history. Huyghe and Mugnier (1995) argue that up to 2300 m of Late Jurassic to Cretaceous section has been removed by erosion. This missing section is restored during the back-stripping. For a tectonic subsidence-driven extensional model, assuming a water-free upper surface, back-stripping shows a gradual Mesozoic subsidence of up to 1100 m. A subsequent inversion episode is predicted to have occurred, causing a tectonic uplift of approximately 600 m and the removal of up to 2300 m of sediment.

High subsidence rates observed in wells located in the Broad Fourteens Basin have led to the adoption of a two phase model of uniform lithospheric extension, with rifting during Triassic to Early Jurassic (251–178 Ma) and during Late Jurassic to Late Cretaceous (157.1–88.5 Ma), respectively. Adopting these two phases of extension during forward modelling studies for the Broad Fourteens basin (Van Wees et al., 1996a) resulted in a cumulative stretching factor (\(\delta = \beta\)) of 1.29. During the modelling, inversion is assumed to occur immediately after the last extension interval (88.5–57 Ma). A stretching factor of 0.847 (\(\delta = \beta\)) equivalent to 15% shortening has been adopted for this inversion period.

Fig. 10 presents the model predictions and shows a correlation between extensional phases and integrated lithosphere strength. Phases of extension are accompanied by minor reductions in integrated strength and inversion is accompanied by a significant increase of integrated strength. These strength changes are the result of heating caused by lithospheric extension and cooling as a result of lithospheric compression, respectively.

The modelling results shown in Fig. 10 agree with previous studies that have shown that the prediction of a basin locking up, particularly during inversion, does not correspond with long-term observations of basins subjected to multiple phases of extension and inversion (Van Wees and Stephenson, 1995; Ziegler et al., 1995). It appears that permanent zones of crustal weakness are the principal mechanism for basin reactivation at a lithospheric scale (Ziegler et al., 1995). For upper crustal levels, weakening has been attributed to pre-existing weak faults with a reduced friction angle (e.g. Van Wees and Stephenson, 1995; Ziegler et al., 1995). Analogue and numerical models incorporating pre-existing weak faults (e.g. Mandl, 1988; McClay, 1989; Sassi et al., 1993; Brun and Nalpas, 1996) have shown to be able to derive results in agreement with observations of reactivated border faults in the Netherlands.

Weakening of pre-existing faults by a reduced friction angle has a significant effect on the lithospheric strength as long as the reduction in friction...
Fig. 11. Location map and geological section of the Roer Valley Graben (section after Geluk et al., 1995). Red lines depict Tertiary faults, yellow lines Quaternary faults.
angle extends into the upper mantle. Weakening of the upper mantle may also be caused by (1) ductile strain localisation mechanisms such as indicated by upper mantle shear zones (2) presence of rheological weak material as suggested by, e.g. upper mantle reflectors (Ziegler et al., 1998; Van Wees and Beekman, 2000).

6. Finite element modelling results for varying dip of basin boundary faults

The rheological modelling results described in the previous section show a weak coupling of subcrustal and upper crustal deformation for the Broad Fourteens Basin (see also Van Wees and Cloetingh, 1994; Burov and Cloetingh, 1997). Such a rheologically stratified lithosphere causes any sub-basinal deformation to be controlled by movement along the weak upper crustal faults. Thus, an intimate interaction between the upper and lower crustal rheologies and sedimentary basin infill must exist. Geo-mechanical models incorporating these rheological concepts (Van Wees et al., 1996a,b; Burov and Cloetingh, 1997) enable study of near-surface tectonic processes which are particularly relevant when investigating geomorphology, seismic hazards and post-seismic slip events.

The geometry and relative weakness of crustal scale faults is largely dependent on the preceding basin history and is particularly important in these models (Van Wees et al., 1996a,b). The elasto-plastic finite element DIANA code (DIANA, 1990) has been used to model the upper crustal and basin architecture of the Roer Valley Graben and illustrates the effects of planar faults with varying extent and properties in the upper crust. The modelling is based on a recently published cross-section of the basin architecture (Fig. 11, Geluk et al., 1995). Conjugate border faults, the Feldbiss Fault and Peel Boundary Fault have been neo-tectonically active and delimit the section. A compilation of hypocentre and focal mechanism data for the Roermond earthquake of 1992 by Camelbeeck et al. (1994) showed that the active fault plane of the Peel fault exhibits normal movement, is dipping SW at 50–70° and extends to a depth of 17 km. Both Roer Valley Graben border faults exhibit a concentration of fault activity during the Mesozoic and Cainozoic (Figs. 7, 8 and 11). Two minor upper crustal faults are associated with the border faults although they show significantly less movement during the Mesozoic and Cainozoic. Maps of the base of both the Tertiary and Quaternary (Fig. 11) show an alignment of seismic activity along the strikes of the Peel Boundary Fault and Feldbiss Fault.

A 2D finite element model, in which the four weak planar faults mentioned above are represented, has been used to investigate how changes in the extent of a fault as a function of fault dip and its frictional properties affects basin deformation. A Mohr–Coulomb plastic response is assumed for the upper crust, the sedimentary cover and frictional behaviour of the faults. Within the models, several values for the friction angles for the sedimentary cover and the basement, as well as the fault dip,
Fig. 13. Finite element modelling results for the Roer Valley section for varying dip in boundary fault, and various values for friction angle of the major faults.
extent of the depth of the fault and frictional properties of the fault are used. A characteristic model configuration with typical geomechanical material properties is given in Fig. 12.

The model is extended horizontally by approximately 200 m, with the base of the model being fixed in the vertical direction. This extension is thought to be representative of neo-tectonic movements (Late Tertiary and Quaternary) of the subsurface. The modelling results of the effects of stress and strain induced by movement along a pre-existing fault are compared with observations.

The model results show that reactivation of pre-existing faults is capable to explain the observed basin deformation (Fig. 13). The relative distribution of fault motion is most sensitive to the extent of a fault and least sensitive to the frictional properties of a fault (Fig. 14). The concentration of deformation on the border faults may be attributed to either the extent of the secondary faults being considerably less than those of the border faults (50° fault dip) or by assuming that the angle of friction parameter of the secondary faults is considerably less than that of the border faults (70° fault dip).

These finite element modelling results show that weak crustal border faults can exert a major influence on basin deformation. The extent of pre-existing weak zones appears to play an important role in the distribution of deformation. This implies that large displacements accommodated by large faults cannot be directly attributed to a relative weakness of these large faults compared to the small faults. However, the repeated localisation and coalescence of deformation along specific faults clearly indicates that a basin area bounded by such faults is relatively weak compared to its surroundings.

6.1. Quaternary fault displacement migration

Recent studies on Quaternary fault motions (Houtgast and van Balen, 2000) indicate that the pattern of cumulative displacement along the boundary faults of the Roer Valley Graben is diverse during discrete time intervals. The Feldbiss Fault, located southwest of the Roer Valley Graben, is characterised by a migration of the maximum vertical displacement from the southeast towards the northwest and vice versa during the Quaternary. The Peel Boundary Fault, located northeast of the Roer Valley Graben, exhibits a relatively ‘stationary’ behaviour considering the vertical displacement. This pattern of migration can be attributed to individual events (e.g. earthquakes or Tertiary clay compaction-driven subsidence) which on longer time scales coalesce into a smooth cumulative pattern or a dextral strike-slip mechanism that subsequently causes extension.

Due to the high variability of fault movements on a short time-scale (i.e. Quaternary), the finite element modelling of the Roer Valley Graben is not able to reproduce these short duration events because of modelling limitations.

Furthermore, Houtgast and van Balen (2000) conclude a causal relationship between the coinciding Tertiary and Quaternary depocentres, therefore implying that identical faults have been active creating the depocentres. It is interesting to note that the ‘Variscan’ Peel Boundary Fault, the Feldbiss Fault and the faults bounding the Broad Fourteens Basin...
display a continuous tectonic activity during the Quaternary and present-day.

6.2. Depth variations and neotectonics

The finite element models described above show significant variation of fault throw, footwall and hangingwall displacement, with depth. In the models presented above, weak faults that do not extend to the surface induce normal drag near the surface that gradually changes into reverse drag at depth. The upper region of normal drag increases in width and vertical extent with increasing depth of the fault tip. The normal drag predicted to occur at the surface for the Roer Valley Graben is in close agreement with recent observations of fault movement (Fig. 15). Conventional kinematic and flexural models of upper crustal faulting do not generate a variation in fault throw and footwall and hangingwall displacement. Furthermore, they predict reverse drag near the surface and normal drag at depth, in contrast to our modelling result (Fig. 14, lower panel). The normal faults depicted in the finite element modelling are able to sole out in low strength non-faulted sediments and reproduce a more realistic set of tectonic features for the Netherlands region. The ability of mimicking other tectonic features, such as growth faulting, indicates that conventional models based on reverse drag may need revision (Fig. 15).

7. Summary and discussion

In this paper we have investigated the consequences of neotectonic reactivation of the fault structures extending across the Netherlands from the Roer Valley Graben in the southeast to the Broad Fourteens basin in the northwest. Rheological modelling of the evolution of the Broad Fourteens Basin clearly suggests that a permanent weakening of the lithosphere exists and that deformation is concentrated on the basin bounding faults. Studies of reactivation along pre-existing faults (Dronkers and Mrozek, 1991; Brun and Nalpas, 1996; Nalpas et al., 1995) (e.g. the Broad Fourteens Basin) have shown that reactivation of pre-existing features occurs on different temporal and spatial scales. Analogue modelling results (Brun and Nalpas, 1996; Nalpas et al., 1995) suggest that inversion of pre-existing faults is accompanied by shallow reverse faults above the inverted graben bounding faults. This highlights the important role (sub-) basin bounding faults as supported by the rheological modelling presented here. The Cainozoic faulting and observed recent seismicity is generally limited to the areas surrounding pre-existing border faults. If, as suggested here, lithospheric weakening is a long-lasting feature, neotectonic activity documented in intraplate areas must be affected by lithospheric memory.

We have shown here the importance of a quantitative linkage between bulk lithosphere rheological models and geomechanical models, so that a better understanding of strain localisation and seismic hazard zonation at or near the surface in neotectonically active areas in the Netherlands can be obtained. Of fundamental importance in quantifying localisation phenomena in present-day deformation are detailed constraints, e.g. lithospheric decoupling and frictional behaviour of faults, on the tectonic grain at mid- and deep crustal levels.
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References

Henk, A., 1999. Did the Variscides collapse or were they torn apart? A quantitative evaluation of the driving forces for post-convergent extension in central Europe. Tectonics 18 (5), 774–792.


Van Wees, J.D., Cloetingh, S., Beeckman, F., 1997. (Neo)cratonic and vertical motions in the Netherlands and surrounding areas: the importance of understanding rheology and preceding basin history. Aardkundige Mededelingen X, 185–188.

Van Wijhe, D.H., 1987. The structural evolution of the Broad...


